A Study on Reduction of Galvanomagnetic Effects in Spin Pumping Measurement

論 文 内 容 要 旨

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学位論文の 題　　目	A Study on Reduction of Galvanomagnetic Effects in Spin Pumping Measurement (スピンポンピング測定における電流磁気効果の抑制に関する研究)		

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The DC voltage generation induced by ferromagnetic resonance in a $Co_{75}Fe_{25}$/Pt bilayer film and in a $La_{0.67}Sr_{0.33}MnO_3/SrRuO_3$ epitaxial bilayer film at room temperature has been investigated. The voltage signal due to inverse spin Hall effect and other galvanomagnetic effects such as anisotropic magnetoresistance and anomalous Hall effect, has been decomposed by using the

difference in the angular dependence. The galvanomagnetic effect seems to be suppressed by using spin injectors possessing lower anisotropic magnetoresistance.

Spin pumping (SP) is an exciting phenomenon where magnetization precession in a ferromagnetic (FM) layer under ferromagnetic resonance (FMR) produces a pure spin current in an adjacent non-magnetic (NM) layer. In NM layer, the spin current is converted into a charge current by the spin–orbit interaction, known as inverse spin Hall effect (ISHE) and produces DC Hall voltage signal. However, galvanomagnetic effects such as anisotropic magnetoresistance (AMR) and anomalous Hall effect (AHE) may be observed simultaneously with ISHE and generate DC voltage due to rectification (rf) effects at FMR in FM. In present study, $Co_{75}Fe_{25}$ has been selected as spin injector because of its AMR is about 10% comparing to $Ni_{81}Fe_{19}$, a widely used spin injector. In addition, $La_{0.67}Sr_{0.33}MnO_3$ has been selected because above room temperature, its magnetoresistance decreases sharply due to heating effect. SP was performed in a $Co_{75}Fe_{25}$/Pt film and in a $La_{0.67}Sr_{0.33}MnO_3$/$SrRuO_3$ (LSMO/SRO) film. The rf effects were expected to be suppressed due to lower AMR of the FM layer. Using the difference in the spectral shape of voltage and in the angular dependence of magnetization among the ISHE, AMR and AHE effects, the ISHE signal was separated from rf signals. The purpose of this experiment was to obtain a dominant ISHE signal over rf effects.

The $Co_{75}Fe_{25}$/Pt film comprises a 10 nm thick $Co_{75}Fe_{25}$ layer and a 10 nm thick Pt layer. First, the Pt layer was sputtered on a thermally oxidized Si substrate and then the $Co_{75}Fe_{25}$ film was prepared by electron beam evaporation in a vacuum, followed by sputtering of a 1.5-nm-thick oxidized Al film on the top as a cap layer. The LSMO/SRO thin films were grown on $SrTiO_3$ (001) substrate by pulsed laser deposition. The SRO film was grown on the LSMO film in situ. The size of $Co_{75}Fe_{25}$/Pt was 0.5 mm × 2 mm and LSMO/SRO was 1 mm × 2 mm rectangular shape.

The samples were placed at the center of a TE_{011} mode cavity where the microwave (MW) magnetic field $\boldsymbol{h}$ is maximized and AHE is minimized. The MW frequency was 9.44 GHz. An external magnetic field $\boldsymbol{H}$ was applied parallel to the film plane, and its direction was rotated to study the magnetization-angle dependence of the DC voltage (V). In $Co_{75}Fe_{25}$/Pt film, the microwave power (P) was kept at 100mW while in LSMO/SRO film the power was applied from 10~100mW.

The $Co_{75}Fe_{25}$/Pt sample was polycrystalline while LSMO/SRO was single crystal. The obtained AMR for $Co_{75}Fe_{25}$ was 0.07%. When $\boldsymbol{H}$ is applied parallel to the film plane, the saturation magnetization ($\mu_0 M_s$) for both $Co_{75}Fe_{25}$/Pt and LSMO/SRO film were about 100mT. From M-T curve, the T_c in LSMO/SRO was found to be about 350K.

In the SP measurement with $Co_{75}Fe_{25}$/Pt sample, a clear spectrum of FMR and V signals are observed at each angle. The sign of V changes with the reversal of the $\boldsymbol{H}$ direction. The magnitude of the peak voltage is largest when the charge current is perpendicular to the magnetization direction, while almost disappears when the charge current is parallel to the magnetization direction. These results are consistent with the ISHE, where a DC electric field is generated perpendicularly to the spatial spin-current direction and also to the spin-polarization direction. To analyze the signal, at first V is separated into symmetric and antisymmetric part. ISHE appears only in symmetric part. Using the difference in the spectral shape and angular dependence of ISHE, AMR and AHE, the ISHE signal (V_{ISHE}) was separated from rf signals ($V_{AMR,}$ V_{AHE}). It has been observed that, the rf signal is mostly from V_{AMR} and V_{ISHE} is clearly dominant over V_{AMR}.

In the SP measurement with LSMO/SRO, it is also observed that the sign of V changes by reversing the direction of $\boldsymbol{H}$ while the magnitude is the same which is consistent with ISHE. Moreover, with the increase in P from 10 to 100mW, the voltage peak shifts to higher resonance field which suggest a monotonic decrease in $\mu_0 M_s$ according to Kittel's formula. However, V reaches its maximum at 75mW and then decreases. Heating effects by absorbing MW increases the sample temperature toward the Curie temperature (T_c) of LSMO. Therefore, $\mu_0 M_s$ decreases and affects V generation. To obtain the efficiency of ISHE, P dependence of Q_P ($\equiv V_{ISHE}/V_{AMR}$) is obtained. It has been observed that, Q_P increases with P. This indicates that ISHE becomes dominant at higher P level because AMR is suppressed due to the decrease in magnetoresistance at higher temperature.

In summary, DC voltage induced by FMR in a $Co_{75}Fe_{25}$/Pt system and LSMO/SRO bilayer system using a TE_{011} cylindrical microwave cavity in an in-plane setup have been studied. The DC voltage signals were decomposed into symmetric and anti-symmetric components and contributions from ISHE, AMR and AHE were separated using a theoretical model. It has been observed that, a dominant inverse spin Hall voltage signal can be generated by suppressing the magnetoresistance of the spin injector either by choosing a low AMR material (ex. $Co_{75}Fe_{25}$) or by spin pumping nearby the T_c (ex. LSMO) of the spin injector. It is expected that, these findings may open up a new route to spintronic applications.

論文審査の結果の要旨

スピントロニクスにおいて、スピン流の理解とその利用が重要な課題となっており、スピン流の生成・検出実験が盛んに行われてきた。スピン流生成の汎用的な方法に、磁性体/金属複合膜にマイクロ波を照射し、磁性体層の磁化歳差運動を励起させ、この運動と界面磁気交換相互作用により金属層にスピン流を注入する方法がある。この方法はスピンポンピング効果と呼ばれており、生成されたスピン流は金属層の逆スピンホール効果によって電圧に変換して検出することができる。しかし、スピンポンピング効果の実験においては専ら磁性絶縁体が利用されており、広範囲の金属膜と組み合わせが可能な金属磁性体の利用は困難であった。これは、金属磁性体は一般に異方性磁気抵抗効果や異常ホール効果を示すため、マイクロ波照射によって強い整流電場が生じてしまうことに起因しており、この整流電場と逆スピンホール効果の信号を分離して定量することは困難であった。

本研究では、スピンポンピング実験の磁場角度依存性を精密に測定することで、異方性磁気抵抗効果や異常ホール効果の信号と逆スピンホール効果の信号を分離する実験を行った。その結果、金属磁性体にもかかわらず、整流電場による寄与を殆ど含まないスピンポンピング誘起逆スピンホール効果を示す系を発見した。この方法を応用し、ペロブスカイト型マンガン酸化物におけるスピンポンピング信号の異常なマイクロ波パワー依存性が、強磁性相転移温度におけるスピンポンピングの消失に対応していることを明らかにした。

本論文は全５章から構成される。第１章では、本研究の背景と目的について述べている。第２章では、スピン流や磁化ダイナミクスに関連する物理現象について概説している。第３章では、実験に用いた材料の物性や薄膜試料の作製方法、スピンポンピング効果の測定法について述べている。第４章では、CoFe 合金/Pt 二層膜、ペロブスカイト型導電性酸化物二層膜におけるスピンポンピング効果の実験結果を報告している。これらの系における起電力の磁場角度依存性やマイクロ波パワー依存性を詳細に測定・解析することで、スピンポンピング誘起逆スピンホール効果とマイクロ波誘起整流電場の分離・定量が実現されている。第５章では、本研究の結論がまとめられている。

Haidar, S. M 提出の論文は、マイクロ波照射に伴う整流電場が十分に抑制され、スピン流信号を純粋に取り出すことが可能なスピンポンピング法を開発したものであり、スピン流の基礎学理の構築に寄与するものと評価できる。この成果は、提出者の S. M. Haidar が学識と自立して研究する能力を有することを示すと判定される。よって、S. M. Haidar 氏提出の博士論文は，博士（理学）の学位論文として合格と認める。